

Measurement of CP violating phase ϕ_s and control of penguin
pollution at LHCbWALAA KANSO
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The study of CP violation in B_s^0 oscillations is a key measurement at the LHCb experiment. In this document, we discuss the latest LHCb results on the CP-violating phase, called ϕ_s , using $B_s^0 \rightarrow J/\psi K^- K^+$ and $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ channels. To conclude on the presence of New Physics in ϕ_s , the estimation of the sub-dominant contributions from the Standard Model becomes crucial now. We outline a method to estimate the contribution of penguin diagrams in ϕ_s . Branching fractions and upper limits of $B_{(s)}^0 \rightarrow J/\psi K_S^0 h^{(\prime)+} h^-$ ($h^{(\prime)} = K, \pi$) modes are presented.

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1 Introduction

The interference between B_s^0 mesons decaying directly via $b \rightarrow c\bar{c}s$ transitions to CP eigenstates and those decaying after B_s^0 - \bar{B}_s^0 oscillations gives rise to a CP violating phase called ϕ_s .

Within the Standard Model, the decay can occur via two main topologies: the predominant tree topology and the sub-leading penguin diagram. New Physics processes, e.g., new particles contributing to the box diagrams, can modify the value of ϕ_s :

$$\phi_s^{\text{meas}} = -2\beta_s + \Delta\phi_s^{\text{peng}} + \delta^{\text{NP}}$$

The indirect determination via global fit to experimental data gives:

$-2\beta_s = 2 \arg(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) = -0.0363 \pm 0.0013$ [7]. The theoretical uncertainty on ϕ_s is mainly due to unknown penguin contributions $\Delta\phi_s^{\text{peng}}$. The control of penguin pollution is limited by large theoretical uncertainties. Thus, experimental measurements are very useful to constrain the contribution of penguin diagrams. Therefore, we should estimate $\Delta\phi_s^{\text{peng}}$, otherwise we may incorrectly interpret the Standard Model penguin contributions as signs of New Physics. In Section 2, we summarize the measurement of the CP-violating phase ϕ_s in $B_s^0 \rightarrow J/\psi K^- K^+$. In Section 3, we report on a recent update of the same measurement using $B_s^0 \rightarrow J/\psi \pi^- \pi^+$. The studies of penguin pollution in ϕ_s and 2β are described in Section 4 and 5 respectively. A recent result on the branching ratio of $B^0(s) \rightarrow J/\psi K_S^0 h^{(\prime)+} h^-$ ($h^{(\prime)} = K, \pi$) modes is shown in Section 6.

2 $B_s^0 \rightarrow J/\psi K^- K^+$

The purpose of this analysis is to mainly measure ϕ_s , the decay width difference $\Delta\Gamma_s$ and Γ_s . $B_s^0 \rightarrow J/\psi[\rightarrow \mu^+\mu^-]\phi[\rightarrow K^+K^-]$ is pseudo-scalar decaying into two vector mesons. The study of this decay requires an angular analysis in order to disentangle CP-odd/CP-even mixture of the final state. After the statistical background subtraction [3], a fit to decay time (t) and three angles in helicity frame ($\Omega = \theta_\mu, \theta_K, \varphi_h$) is performed in six bins of m_{KK} [5]. To account for the detector and selection effects, the decay time acceptance is taken from real data and the angular acceptance is studied in the simulated data. The finite decay time resolution is modelled by a single Gaussian of width $S_{\sigma_t} \times \sigma_t$, where σ_t is the estimated per event decay time uncertainty, and the scale factor, S_{σ_t} , is measured in a sample of prompt $J/\psi \rightarrow \mu^+\mu^-$. The effective resolution is 45 fs for $B_s^0 \rightarrow J/\psi\phi$. The B_s^0 flavour, at production, is determined by the combination of the same side kaon tagger and the opposite side taggers, which gives the overall tagging power: $\epsilon(1 - 2\omega)^2 = (3.13 \pm 0.23)\%$, where ϵ indicates the tagging efficiency, and ω the mistag rate [14]. Using 1 fb⁻¹ of real data collected in 2011, LHCb obtained:

$$\begin{aligned}
\phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst)} \\
\Gamma_s &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)} \\
\Delta\Gamma_s &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)}
\end{aligned}$$

3 $B_s^0 \rightarrow J/\psi \pi^- \pi^+$

Another useful channel to measure ϕ_s is $B_s^0 \rightarrow J/\psi \pi^- \pi^+$. This decay is 97.7% dominated by the CP-odd component, at 95 % C.L [4]. Nevertheless, an angular analysis is needed to obtain the small CP-even component. We performed a six-dimensional fit of B_s^0 and $\pi\pi$ masses, time and the three helicity angles ($m_{B_s^0}$, t , $m_{\pi\pi}$, Ω). The decay time acceptance is determined in $B^0 \rightarrow J/\psi K^{*0}$ channel and simulation, while $\Delta\Gamma_s$ and Γ_s are taken from $B_s^0 \rightarrow J/\psi \phi$. This analysis aims to measure ϕ_s and $|\lambda|$, related to the direct CP violation. By following the same methodology as in $B_s^0 \rightarrow J/\psi \phi$ channel to determine the effective decay time resolution, we obtained: 40fs. The tagging algorithm achieved a power of: $\epsilon(1-2\omega)^2 = (3.89 \pm 0.25)\%$. It is found that five interfering $\pi^+\pi^-$ states are required to describe the data. These include the dominant $f_0(980)$, as well as the $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2'(1525)$. The resulting decomposition of the $\pi^+\pi^-$ invariant mass spectrum is shown in (fig. 1(a)). The projections of angular distributions are shown in fig. 2.

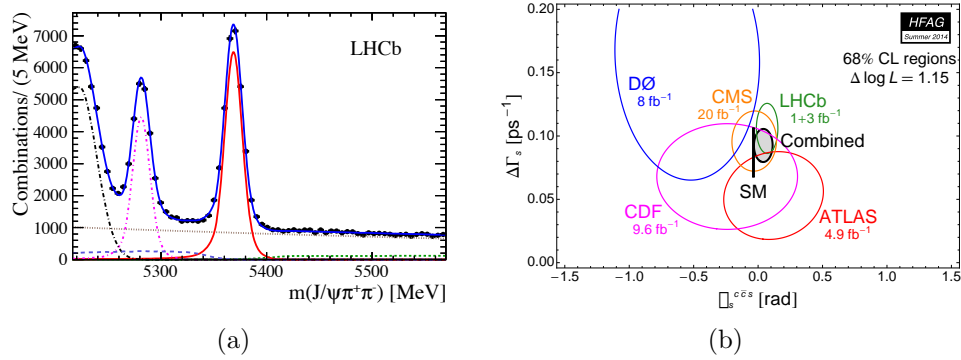


Figure 1: (a): Invariant mass of $J/\psi \pi^\pm \pi^\mp$. The (red) solid line shows the B_s^0 , the (brown) dotted line shows the exponential combinatorial background, the (green) short-dashed line shows the B^\pm background, the (magenta) dot-dashed line shows the B^0 signal, the (light blue) dashed line represents some misreconstructed decays, the (black) dot-dashed line is the $B^0 \rightarrow J/\psi K^\pm \pi^\mp$ reflection and the (blue) solid line is the total. (b): Unofficial overview of the current experimental constraints in the ϕ_s - $\Delta\Gamma_s$ plane, modified compared to the original [8] to include these results as well as the summer 2014 updates from Atlas [10] and CMS [9].

LHCb analysed 3 fb^{-1} of $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ collected in 2011 and 2012. Assuming that there is no direct CP-violation ($|\lambda| = 1$), the CP violating phase, ϕ_s , is:

$$\phi_s = 0.075 \pm 0.067 \text{ (stat)} \pm 0.008 \text{ (syst)}$$

If the direct CP-violation, represented by $|\lambda|$, is floating, we obtained:

$$\begin{aligned} \phi_s &= 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst)} \\ \lambda &= 0.89 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)} \end{aligned}$$

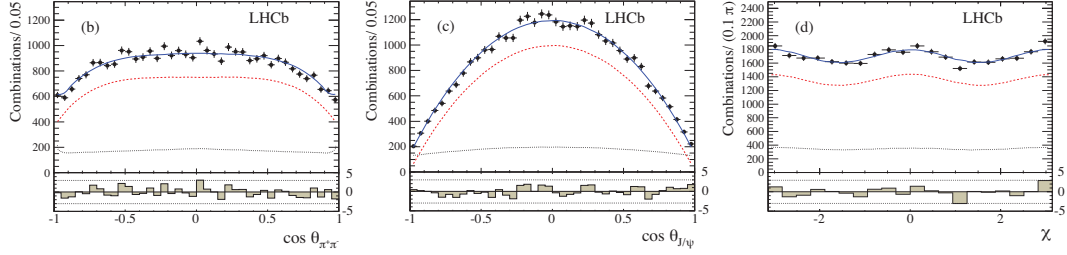


Figure 2: Projections of the three decay angles. The signal fits are shown with (red) dashed lines, the background with a (black) dotted lines, and the (blue) solid lines represent the total fits. The difference between the data and the fits divided by the uncertainty on the data is shown below.

A preliminary combination of $3 \text{ fb}^{-1} B_s^0 \rightarrow J/\psi \pi^- \pi^+$ with $1 \text{ fb}^{-1} B_s^0 \rightarrow J/\psi K^- K^+$, gives:

$$\phi_s = 0.070 \pm 0.054 \pm 0.011$$

This measurement is consistent with the Standard Model but there is still room for New Physics. A comparison of the LHCb result with those of other experiments is shown in fig. 1(b)

4 Estimating penguin pollution in ϕ_s with $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$

A sample of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ is taken as a control channel because the penguin diagrams are not suppressed in this decay. While in the $B_s^0 \rightarrow J/\psi \phi$ channel, the penguin process is suppressed, by $\lambda^2 \sim 0.05$, relative to tree diagram. a_i and θ_i are defined as penguin's parameter for $B_s^0 \rightarrow J/\psi \phi$ [2]. There are two penguin parameters for each of the three polarizations of final states: $i = 0, \perp, \parallel$: $a_i e^{i\theta_i} = (1 - \frac{\lambda^2}{2}) |V_{ub}/(\lambda V_{cb})| \left[\frac{P_u^i + P_t^i}{T_c^i + P_c^i - P_t^i} \right]$. With $\lambda \sim 0.22$, penguin amplitude is: $P_q, q = u, t, c$, and the tree amplitude is represented by: T_c . a'_i and θ'_i are the penguin parameters for $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$. In order to connect both channels, penguin parameters in $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$, are supposed equal, using the approximations of SU(3) flavour (quarks u, d, s are identical):

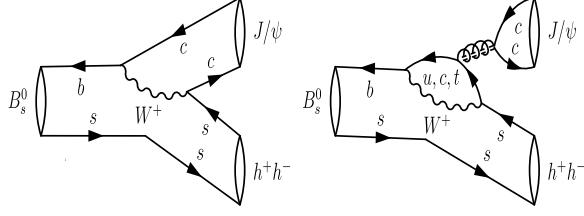


Figure 3: Feynman diagrams contributing to the decay $B_s^0 \rightarrow J/\psi h h^-$ within the Standard Model. Left: tree; right: penguins.

$$a_i = a'_i, \quad \theta_i = \theta'_i$$

Therefore, a shift on ϕ_s due to penguin diagrams, is calculated for each polarization: $\tan(\Delta\phi_s^{i,\text{peng}}) = \frac{2\epsilon a_i \cos \theta_i \sin \gamma + \epsilon^2 a_i^2 \sin 2\gamma}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2 \cos 2\gamma}$, where $\epsilon = \frac{\lambda^2}{1 - \lambda^2}$. From the experimental point of view, there are two observables for each polarization ($i = 0, \perp, \parallel$): The first one, H_i , is proportional to the ratio of branching fractions of the 2 channels, multiplied, respectively, by the corresponding polarization fractions. The products of the decay can be in three polarization states: longitudinal, parallel and perpendicular. This requires an angular analysis to disentangle those states. The factor $\left| \frac{\mathcal{A}_i}{\mathcal{A}'_i} \right|^2$ is a critical SU(3) breaking factor calculated theoretically with a big error.

$$H_i = \frac{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2} = \frac{1 - \lambda^2}{\lambda^2} \left| \frac{\mathcal{A}_i}{\mathcal{A}'_i} \right|^2 \frac{f_{J/\psi \bar{K}^{*0}}^i \cdot BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{f_{J/\psi \phi}^i \cdot BR(B_s^0 \rightarrow J/\psi \phi)} \quad (1)$$

The second observable is the direct CP violation in $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$:

$$A_i^{CP} = \frac{2a_i \sin \theta_i \sin \gamma}{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2} = \frac{\Gamma_{B_s^0}^i - \Gamma_{\bar{B}_s^0}^i}{\Gamma_{B_s^0}^i + \Gamma_{\bar{B}_s^0}^i} \quad (2)$$

H_i and A_i^{CP} form a non trivial system of two equations with two unknowns : a_i and θ_i that lead to the shift on ϕ_s , $\Delta\phi_s^{i,\text{peng}}$. In this channel, an angular analysis is required to calculate the polarization amplitudes. The presence of P and S-wave in the $K\pi$ system has to be studied carefully. Using 0.37 fb^{-1} , a fit to mass, angles has been performed and gave [5]:

$$BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (4.4_{-0.4}^{+0.5} \pm 0.8) \times 10^{-5}$$

$$f_L = 0.50 \pm 0.08 \pm 0.02, \quad f_{\parallel} = 0.19_{-0.08}^{+0.10} \pm 0.02$$

In order to determine penguin pollution in $B_s^0 \rightarrow J/\psi \phi$, a measurement of the direct CP violation, in $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$, is needed. To do so, one has to split the data sample into $K^+\pi^-$ and $K^-\pi^+$. A direct CP violation measurement and an update, with 3 fb^{-1} , of the branching ratio and polarization fractions are ongoing.

5 Estimating penguin pollution in 2β with $B_s^0 \rightarrow J/\psi K_S^0$

$B_s^0 \rightarrow J/\psi K_S^0$ is the ultimate tool for controlling penguin diagrams in $B^0 \rightarrow J/\psi K_S^0$. This requires a CP analysis in $B_s^0 \rightarrow J/\psi K_S^0$ [2]. LHCb published a previous analysis of $B_s^0 \rightarrow J/\psi K_S^0$ with 1 fb^{-1} of real data [6]:

$$BR(B_s^0 \rightarrow J/\psi K_S^0) = (1.97 \pm 0.23) \times 10^{-5}, \quad \tau^{eff} = 1.75 \pm 0.12(\text{stat}) \pm 0.07(\text{syst}) \text{ ps}$$

A CP analysis is ongoing, as well as an update of the branching ratio with full LHC run 1 data.

6 $B_{(s)}^0 \rightarrow J/\psi K_S^0 h^{(\prime)+} h^-$ ($h^{(\prime)} = K, \pi$)

This analysis could help, with high statistics, in the measurement of ϕ_s . It's also interesting for spectroscopy measurements and the search for exotics [1].

New branching fraction measurements of $B_{(s)}^0 \rightarrow J/\psi K_S^0 h^{(\prime)+} h^-$ ($h^{(\prime)} = K, \pi$) have been performed with 1 fb^{-1} of real data. The channel $B^0 \rightarrow J/\psi K_S^0 \pi \pi$ is confirmed and first observations of $B_s^0 \rightarrow J/\psi K_S^0 K \pi$ and $B^0 \rightarrow J/\psi K_S^0 K K$ are published with more than 7σ .

In the first place, $B^0 \rightarrow J/\psi K_S^0 \pi \pi$ has been measured relative to $B^0 \rightarrow J/\psi K_S^0$. Using $B^0 \rightarrow J/\psi K_S^0 \pi \pi$ updated branching fraction, all others modes are measured as you can see below:

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow J/\psi \bar{K}^0 K^\pm \pi^\mp) &= (11 \pm 5(\text{stat}) \pm 3(\text{syst}) \pm 1(\text{PDG})) \times 10^{-6}, \\ &< 21 \times 10^{-6} \text{ at } 90\% \text{ CL}, \\ &< 24 \times 10^{-6} \text{ at } 95\% \text{ CL}, \\ \mathcal{B}(B^0 \rightarrow J/\psi K^0 K^+ K^-) &= (20.2 \pm 4.3(\text{stat}) \pm 1.7(\text{syst}) \pm 0.8(\text{PDG})) \times 10^{-6}, \\ \mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0 \pi^+ \pi^-) &= (2.4 \pm 1.4(\text{stat}) \pm 0.8(\text{syst}) \pm 0.1(f_s/f_d) \pm 0.1(\text{PDG})) \times 10^{-5}, \\ &< 4.4 \times 10^{-5} \text{ at } 90\% \text{ CL}, \\ &< 5.0 \times 10^{-5} \text{ at } 95\% \text{ CL}, \\ \mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0 K^\pm \pi^\mp) &= (91 \pm 6(\text{stat}) \pm 6(\text{syst}) \pm 3(f_s/f_d) \pm 3(\text{PDG})) \times 10^{-5}, \\ \mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^0 K^+ K^-) &= (5 \pm 9(\text{stat}) \pm 2(\text{syst}) \pm 1(f_s/f_d)) \times 10^{-6}, \\ &< 12 \times 10^{-6} \text{ at } 90\% \text{ CL}, \\ &< 14 \times 10^{-6} \text{ at } 95\% \text{ CL}, \end{aligned}$$

7 Epilogue

While completing these proceedings, several important new results have been obtained. LHCb updated the measurement of the CP-violating phase ϕ_s with 3 fb^{-1} [12], and put limits on penguin effects in ϕ_s [11]. The shift in ϕ_s is limited to be within

the interval $[-1.05^\circ, 1.18^\circ]$ at 95% C.L. HFAG collaboration updated the the ϕ_s - $\Delta\Gamma_s$ plane [13].

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References

- [1] R. Aaij *et al.* [LHCb Collaboration], “Observation of the $B_s^0 \rightarrow J/\psi K_s^0 K^\pm \pi^\mp$ decay,” JHEP **1407**, 140 (2014) [arXiv:1405.3219 [hep-ex]].
- [2] S. Faller, R. Fleischer and T. Mannel, “Precision Physics with $B_s^0 \rightarrow J/\psi \phi$ at the LHC: The Quest for New Physics,” Phys. Rev. D **79** (2009) 014005 [arXiv:0810.4248 [hep-ph]].
- [3] Yuehong Xie, “sFit: a method for background subtraction in maximum likelihood fit,” [arXiv:0905.0724].
- [4] R. Aaij *et al.* [LHCb Collaboration], “Measurement of the CP-violating phase ϕ_s in $\bar{B}_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays,” Phys. Lett. B **736**, 186 (2014) [arXiv:1405.4140 [hep-ex]].
- [5] R. Aaij *et al.* [LHCb Collaboration], “Measurement of the $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ branching fraction and angular amplitudes,” Phys. Rev. D **86**, 071102 (2012) [arXiv:1208.0738 [hep-ex]].
- [6] R. Aaij *et al.* [LHCb Collaboration], “Measurement of the effective $B_s^0 \rightarrow J/\psi K_S^0$ lifetime,” Nucl. Phys. B **873**, 275 (2013) [arXiv:1304.4500 [hep-ex]].
- [7] J. Charles, O. Deschamps, S. Descotes-Genon, R. Itoh, H. Lacker, A. Menzel, S. Monteil and V. Niess *et al.*, Phys. Rev. D **84**, 033005 (2011) [arXiv:1106.4041 [hep-ph]].
- [8] Y. Amhis *et al.* [Heavy Flavor Averaging Group Collaboration], “Averages of B-Hadron, C-Hadron, and tau-lepton properties as of early 2012,” arXiv:1207.1158 [hep-ex].
- [9] CMS Collaboration [CMS Collaboration], “Measurement of the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the B_s to $J/\psi \Phi(1020)$ decay channel,” CMS-PAS-BPH-13-012.

- [10] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **90**, 052007 (2014) [arXiv:1407.1796 [hep-ex]].
- [11] R. Aaij *et al.* [LHCb Collaboration], “Measurement of the CP-violating phase β in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays and limits on penguin effects,” arXiv:1411.1634 [hep-ex].
- [12] R. Aaij *et al.* [LHCb Collaboration], “Precision measurement of CP violation in $B_s^0 \rightarrow J/\psi K^- K^+$ decays,” arXiv:1411.3104.
- [13] Y. Amhis *et al.*, “Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012,” arXiv:1207.1158 and online update at <http://www.slac.stanford.edu/xorg/hfag>
- [14] R. Aaij *et al.* [LHCb Collaboration], “Measurement of CP violation and the B_s^0 meson decay width difference with $B_s^0 \rightarrow J/K^+ K^-$ and $B_s^0 \rightarrow J/\psi^{+-}$ decays,” Phys. Rev. D **87**, no. 11, 112010 (2013) [arXiv:1304.2600 [hep-ex]].